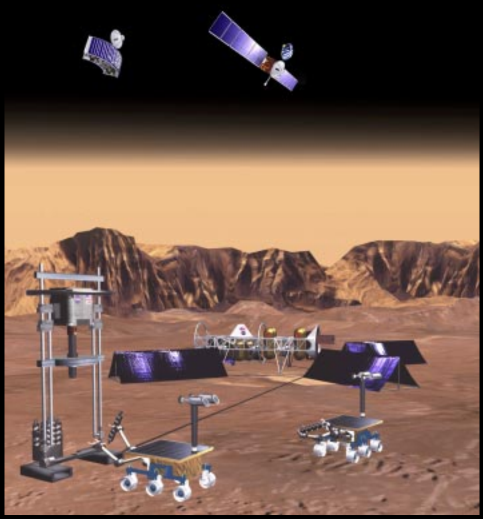
2001 Research Update



Exploration Systems Autonomy

Jet Propulsion Laboratory

We provide computing and autonomy technologies to enable the coming generations of highly autonomous and scientifically productive deep space missions.

We enable Autonomous Space Exploration Systems by conducting long-range research and development of information and computing technologies and applying revolutionary advances of computer science principles to deep space exploration. We provide software systems, new algorithms, advanced computational approaches and new discoveries that enable new types of capability and new levels of productivity and robustness for JPL and NASA's scientific missions, with an emphasis on autonomous exploration and discovery.

DR. ANNA TAVORMINA
MANAGER

EXPLORATION SYSTEMS
AUTONOMY SECTION

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Award-Winning Technologists

As humankind extends its presence farther through the Cosmos, into often unpredictable and unexplored environments, a new breed of scientific spacecraft will be required. Due to light-time communication delays inherent in deep-space travel and the sophistication of future exploration missions, direct human control of the spacecraft will often be infeasible. These future robotic explorers must be capable of planning and executing their own activities, recovering from system faults, assessing and maintaining their own health, responding optimally to unanticipated scientific opportunities, and determining which data are most important to send back to Earth.

Systems autonomy provides the capabilities needed to accomplish these future missions. Missions that involve submarine exploration of the oceans believed to lie beneath the icy crust of Europa, colonies of intelligent collaborating robots on Mars, constellations of actively cooperating spacecraft,

Exploration Systems Autonomy

and expeditions into interstellar space will all require onboard system-level decision-making to ensure mission success and maximal scientific return.

The JPL Exploration Systems Autonomy Section develops technologies needed to meet these challenges, spanning the lifecycle from basic research and conceptual development through system maturation and incorporation into missions. Whether intended for use on board or on Earth, our research addresses the key system-level functions and capabilities necessary to plan, conduct, and evaluate the scientific return of deep-space and near-Earth exploration missions.

The members of the Exploration Systems Autonomy Section are dedicated to making significant contributions to NASA's mission of increasing humanity's knowledge and understanding of the Universe. In the following pages, we will share some recent results of our research, covering topics in automated planning and scheduling; distributed autonomy; intelligent science data understanding; autonomous system health maintenance; the creation, analysis, and visualization of large data sets; and quantum computing technologies.

We hope you find this publication useful. Please feel free to contact us regarding areas in which our research may be beneficial to you.

Intelligent planning and execution technologies are being developed that enable the commanding of spacecraft with high-level goals rather than detailed sequences. Within the onboard software, the spacecraft possesses the knowledge and reasoning procedures for determining the actions needed to achieve those goals while preserving spacecraft health. The spacecraft continually monitors itself and its environment, and changes its course of action as needed to achieve its goals.

Automated Mission Planning & Execution

CURRENT RESEARCH

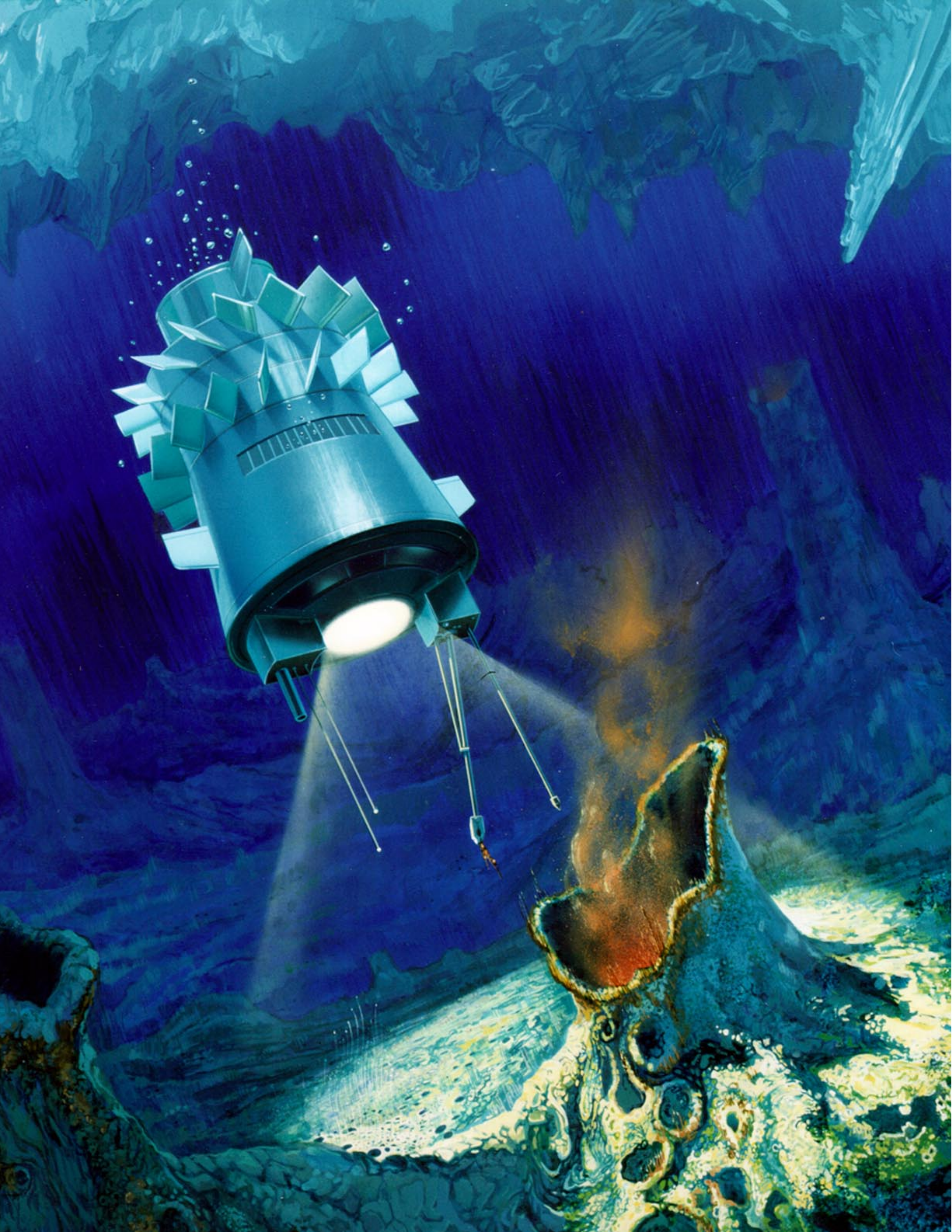
ASPEN Automated Planner

The Automated Scheduling and Planning Environment (ASPEN) is a flexible, reusable application framework for developing automated planning systems. ASPEN automatically generates plans of activities to achieve desired goals while respecting operations constraints involving states, resources, and timing. ASPEN has been applied to ground-based and onboard planning problems such as antenna ground station automation, autonomous spacecraft, rovers, and unpiloted aerial vehicles.

Continuous Planning

An autonomous spacecraft must be able to plan ahead to avoid shortsighted decisions that can lead to failure, yet it must also respond in a timely fashion to dynamic and unpredictable environments.

Artist's rendering of a submersible hydrobot that could be used to explore the ice-covered ocean on Jupiter's large satellite Europa. This mission will require adaptive problem solving — one of our primary research areas in Automated Mission Planning and Execution.



CASPER (Continuous Activity Scheduling Planning Execution and Replanning) uses iterative repair to support continuous modification and updating of a current working plan in light of changing operating context. This continuous planning approach enables CASPER to respond to anomalies or opportunities in a rapid timescale (tens of seconds on a flight processor).

Plan Optimization

The role of a planner is to generate low-level activities that accomplish goals and maximize objectives within the operational constraints of the system. Current research in automated planning has more focus on managing constraints and less on maximizing objectives. However, for many applications, many of the requirements are preferences rather than constraints, and increasing plan quality is a dominant part of the planning process.

We are developing a structured representation of plan quality that is capable of encoding preferences that are common in NASA planning problems. This includes preferences for maximizing science in a restricted window and minimizing time spent in particular undesirable states. We have shown that the structure of the preferences can be exploited to efficiently reason about improvements. We are currently extending this framework to integrate shallow and deep improvement methods.

Adaptive Problem Solving

Proposed missions to explore comets and moons will encounter environments that are hostile and unpredictable. Any successful explorer must be able to adapt to a wide range of possible operating conditions in order to survive.

The traditional approach of constructing special-purpose control methods requires information about the environment, which is not available *a priori* for these missions. Adaptive planning uses a flexible problem solver with significant capability to adapt its behavior. Using adaptive problem solving, a spacecraft uses reinforcement learning to learn an environment-specific search method.

Adaptive planning algorithms use reinforcement learning to evaluate a set of control strategies so that they can be ranked in terms of their utility for problem instances. A search method will generate new control strategies based on the highest-scoring control strategies of the previous cycle. The cycle then repeats with this new algorithm.

This is a volcanic eruption on Io, a large satellite of Jupiter. With its onboard planning and scheduling capabilities, CASPER can react quickly to this event. With CASPER, a spacecraft can reconfigure itself to capture additional scientific data from such events.

Integrated Planning and Execution

The CLEaR (Closed Loop Execution and Recovery) task is an effort to develop a robust automation control architecture integrating planning and execution technology. This effort is motivated by the desire to create a highly reactive/ responsive goal-based commanding system. In the pursuit of this work, we are developing a framework enabling both declarative and procedural representation to facilitate both near- and long-term deliberative and reactive behavior. To this end, we are integrating the CASPER continuous planner with the Task Definition Language (TDL) developed at Carnegie-Mellon University. This technology is being demonstrated on both prototype planetary rovers and in autonomous control of ground communications stations.

Stochastic Heuristic Search Profiles

Algorithm portfolios are sets of algorithms designed to work synergistically to solve a problem. In a synergistic portfolio, the whole is greater than the sum of its parts: the probability of at least one algorithm succeeding is greater than the sum of the independent success probabilities, due to negative correlations.

Algorithms can be combined within a single run to enable multiple algorithms to solve a single problem instance approaching multistrategy cooperative problem solving. Portfolios containing stochastic algorithms can exploit rapid restarts, which is beneficial for certain problem classes. This research investigates the use of stochastic combinations of search heuristics in the ASPEN planner using the iterative repair framework to improve local search on a wide range of problem domains.

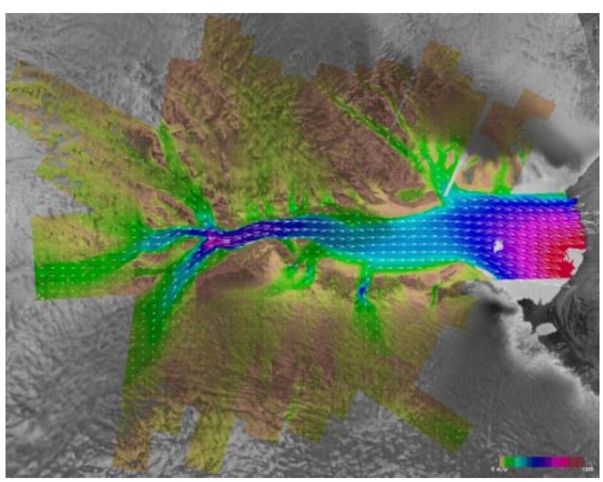
TECHNOLOGY DEPLOYMENTS

Automated Planning for the Modified Antarctic Mapping Mission

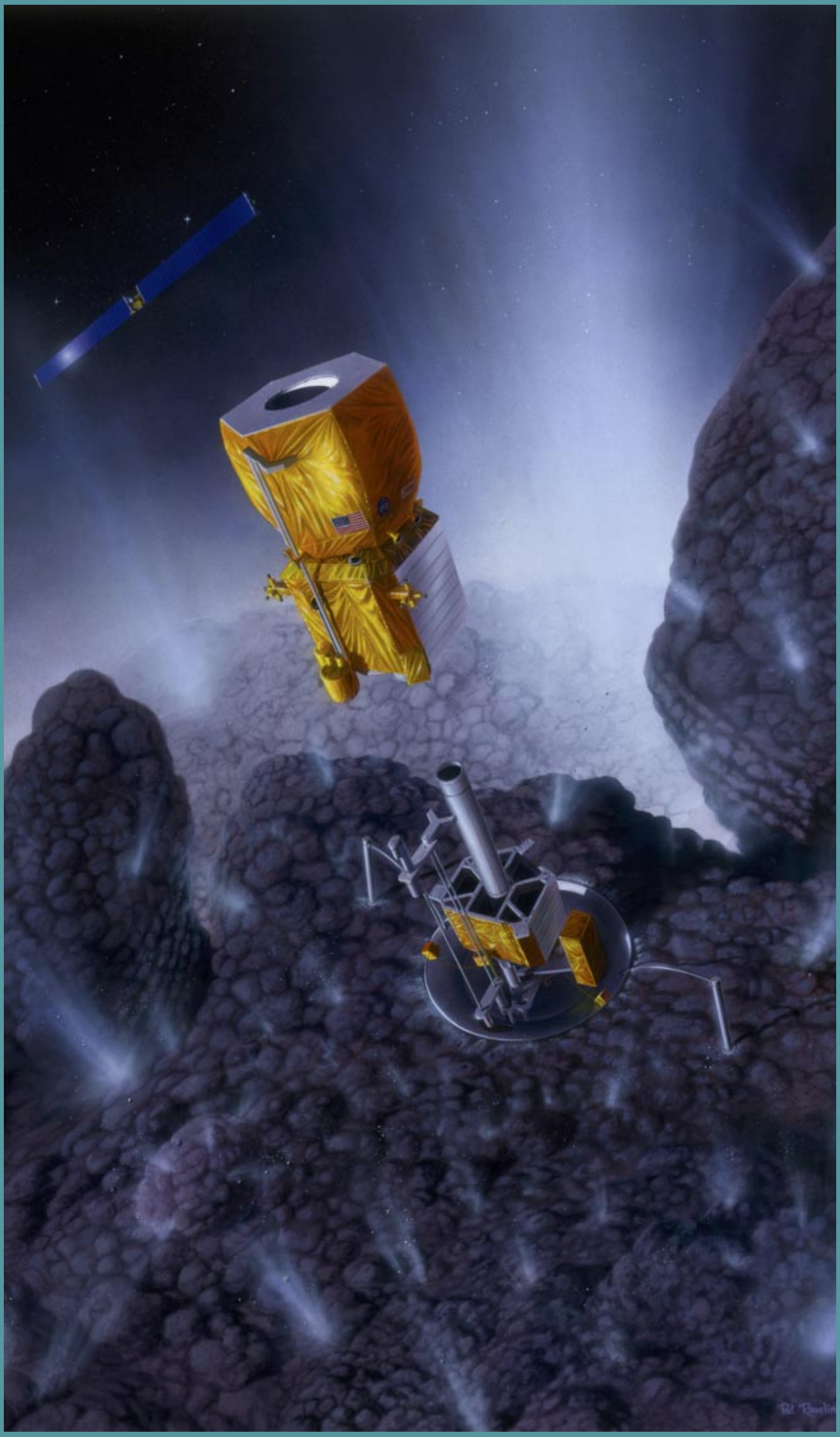
ASPEN automated the mission-planning process for the Modified Antarctic Mapping Mission, a joint mission between NASA and the Canadian Space Agency, which operated from November to December 2000 on RadarSAT. Human planners selected desired observations from a large set of opportunities. The ASPEN system automatically generated the data downlink schedule for these observations, expanded the observations and downlinks into a detailed mission plan, and verified that this detailed plan respected all of the spacecraft operating constraints. The system reduced the mission planning effort to about eight workweeks as opposed to over a work-year for the first Antarctic Mapping Mission, which was of comparable complexity and planned manually.

Three Corner Sat (3CS)

Three Corner Sat (3CS) is a mission of three university nanosatellites scheduled for a space shuttle launch in late 2002. It is a joint project of Arizona State University, the University of Colorado, Boulder, and New Mexico State



Lambert glacier velocity map obtained by the 2000 Antarctic Mapping Mission. Most of the glacier has velocities between 400–800 meters per year, with a slight slowing in the middle section. The smaller confluent glaciers have lower velocities (shown in green) of 100–300 meters per year.



Artist's rendering of a cometary lander, orbiter, and sample return vehicle. Comets pose challenges because the environment on a comet is unknown but expected to be very dynamic.

University. The 3CS mission will demonstrate significant onboard autonomy, including robust execution using the Spacecraft Command Language (SCL), onboard planning using CASPER, and onboard anomaly detection using SELMON (also developed at JPL under the autonomy technology program). CASPER will manage onboard planning and execution of engineering activities (such as communications, calibration, power and other resources), science imaging activities (including data validation, prioritization for downlink), as well as interacting with downlink activities. Within the 3CS mission parameters, CASPER will be able to respond to activity and state updates on a 10-second timescale.

Autonomous Sciencecraft Experiment

The Autonomous Sciencecraft Experiment (ASE) will fly on board the Air Force TechSat-21 constellation scheduled for launch in 2004. ASE autonomously recognizes science opportunities and then will reconfigure the constellation to acquire focused images on subsequent orbits. This onboard recognize-and-replan loop enables the spacecraft to dramatically increase the science per fixed downlink by enabling downlink of only the highest-priority science data. Additionally, ASE enables detection and observation of short-duration science events such as volcanic eruptions, dust storms, supernovae, and solar flares. ASE is a collaboration including JPL, the Air Force Research Laboratory, Interface & Control Systems, Princeton Satellite Systems, Arizona State University, and the University of Arizona.

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NEW TECHNOLOGY/SOFTWARE

- Adaptive Problem Solving (APS) — NTR #21071
- Antarctica Mapping Mission Automated Mission Planner* — NTR #21092 (September 2001)
- Automated Planning and Scheduling Environment (ASPEN), Version 2 — NTR #20299
- Automated Planning and Scheduling for Planetary Rovers — NTR #20574
- Automated Planning for Interferometer Configuration and Control — NTR #21179
- Automated Planning for Mission Design (ASPEN) — NTR #21000
- Closed Loop Execution And Recovery (CLEaR) — NTR #21040
- Continuous Activity Scheduling Planning Execution and Re-planning (CASPER) — NTR #20972
- Goal-Based Fault Tolerance for Space Systems Using the JPL Mission Data System — NTR #21176
- Integrated Planning and Execution for Autonomous Spacecraft — NTR #20590
- Iterative Optimization of Plans* — NTR #20922 (September 2001)
- Program for Evaluating Spacecraft Designs and Missions* — NTR #20492 (May 2001)
- Programming Language for Automated Scheduling and Planning* — NTR #20281
- Test Automation Software for AI Planning Software (PLANCHECKER)* — NTR #21118 (October 2001)
- The Generalized Time Line API: Providing Representational Sufficiency to Planner/Schedulers — NTR #21022

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* *This software is available for commercial licensing. Please contact Don Hart of the California Institute of Technology at (818) 393-3425. For more information on this software, go to* http://www.nasatech.com/Briefs/cs.html. *Items are categorized by release date under the "Calendar" link.*

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Artist's depiction of possible autonomous robotic platforms that may be used to explore the Martian landscape.

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Future NASA missions will involve multiple spacecraft or rovers that must interact with each other to achieve mission goals. Commanding a constellation by issuing individual sequences of timed commands to each spacecraft would not only be cumbersome and expensive, but it would be nearly impossible to command coordinated activities. New autonomy technologies are needed that can operate a constellation as a coordinated entity. Team planning and execution technologies extend single-spacecraft planning and execution technologies to deal with the coordination issues faced by spacecraft constellations and rover fleets.

Distributed Autonomous Systems

CURRENT RESEARCH

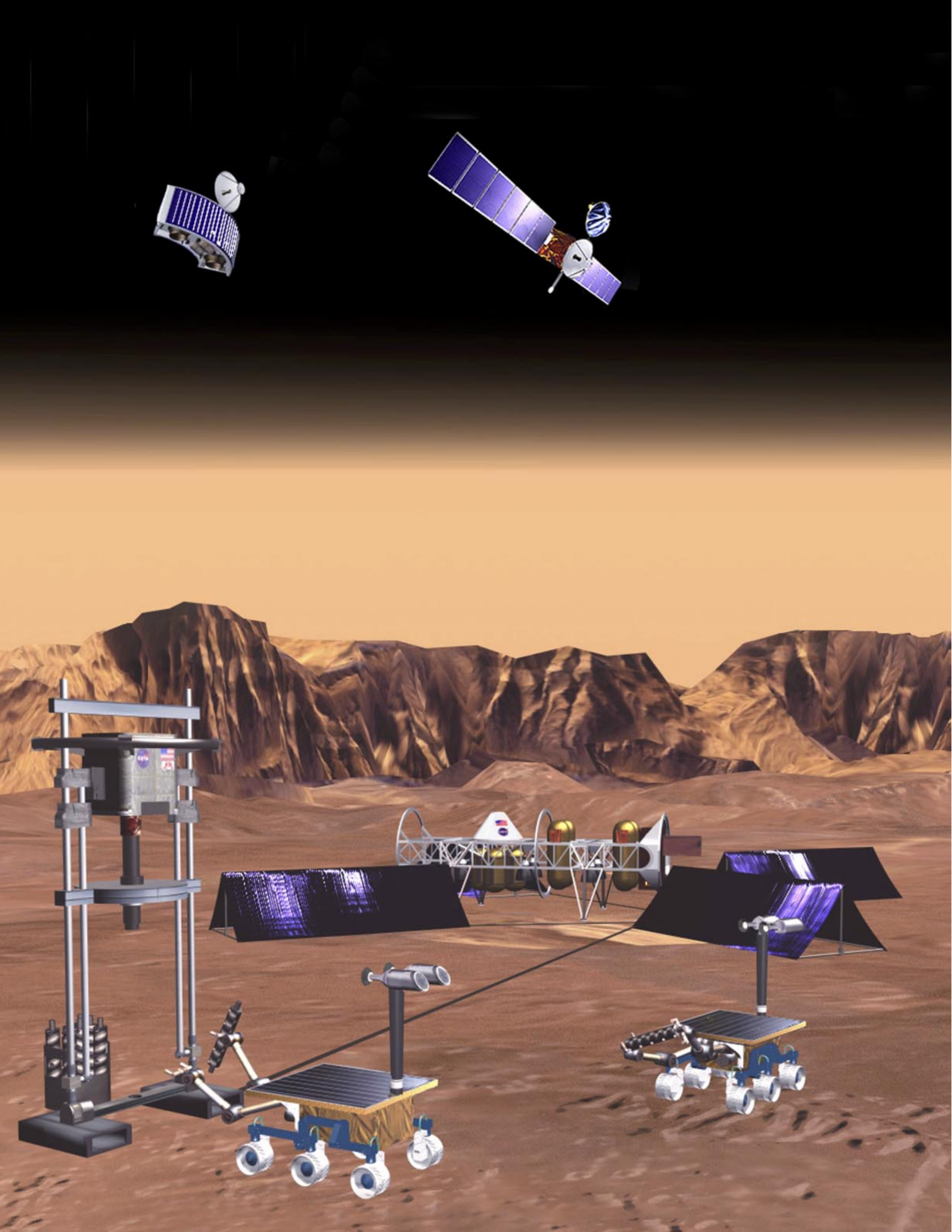
Distributed Goal Management

An autonomous collection of rovers or spacecraft must be able to flexibly determine which robotic entity is responsible for satisfying each mission goal when that goal either arrives from Earth or is generated by some onboard science analysis process. This determination depends both on each entity's specific capabilities and how well it can fit activities to satisfy a new goal into its current schedule. By combining contract network protocols and centralized planning at abstract levels for goal distribution, multiple autonomous spacecraft and rovers can satisfy a collection of observation goals.

Coordinating Local Schedules

While each spacecraft has its own local resources, such as power and data storage, they also share common resources, such as access to a ground station. Without collabora-

Artist's rendering of a robotic outpost on Mars that could be used to explore the surface and drill for water to provide remote fuel synthesis.



tion, local planning decisions can lead to global coordination failures either while trying to access shared resources, or during the performance of joint activities. Each spacecraft's local planner must collaborate with its neighbors in order to avoid these failures. JPL is currently developing techniques to support this type of collaboration. Advanced argumentation-based negotiation research is being combined with studies on iterative repair planning to update coordinated local schedules as unexpected events occur and new goals are introduced.

Coordinating Activity Execution

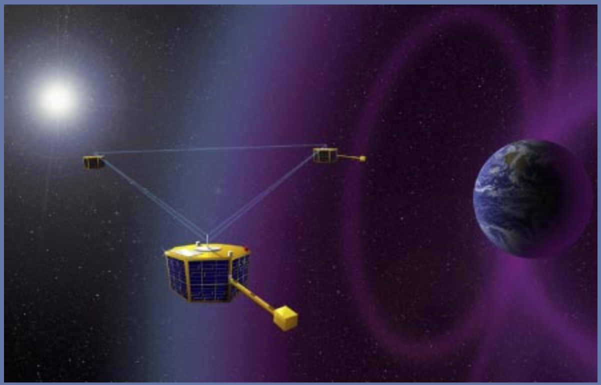
The role of an activity execution system is to robustly actuate a spacecraft's control loops to perform activities within its resource bounds in dynamic, partially understood environments. For activities that span multiple spacecraft, the problem is complicated by control loops that can span multiple spacecraft. Robustly actuating these control loops involves identifying, diagnosing, and responding to anomalies that span one or more spacecraft.

To develop this distributed activity execution system, we are combining techniques from flexible teamwork modeling with mechanisms for onboard mode estimation and distributed command fusion. Where flexible teamwork facilitates techniques for modeling the relationships between cooperative activities, distributed command fusion facilitates mechanisms for implementing and modeling control loops. Mode estimation mechanisms use these models to continually detect and respond to anomalies.

Distributed Onboard Scientist

In addition to coordinating planning and execution tasks for multiple spacecraft or rovers, we are also investigating methods of coordinating autonomous science analysis methods for multiple robotic agents. Future missions will likely utilize teams of rovers, where each rover is responsible for accomplishing a subset of the overall mission science goals. The individual rover then shares its acquired information with the rest of the team. In such a setting, it is desirable to have autonomous rovers that can make decisions on their own as to what exact science data should be collected and returned.

We are currently developing techniques for analyzing collected science data where an onboard analysis system uses image and spectral mineralogical features to help classify different planetary rock types. Analysis is performed using a distributed algorithm where each rover alternates between independently performing computations on its local data and updating the system-wide model though communication among rovers. The resultant global model is used to assemble a new set of observation goals for the rover team, which are passed on to the distributed planning system for goal distribution, command-sequence determination, and execution.



Artist's rendering of a three-spacecraft sensor web for measuring space weather phenomena within the Earth's magnetosphere.

TECHNICAL CONTACTS

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NEW TECHNOLOGY/ SOFTWARE

Contract Methods for Coordination of Multiple Rovers (ASPEN) — NTR #20940

Goal Distribution Approach to Multiple Rover Coordination* — NTR #21031 (May 2001)

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* *This software is available for commercial licensing. Please contact Don Hart of the California Institute of Technology at (818) 393-3425. For more information on this software, go to http://www.nasatech.com/Briefs/cs.html. Items are categorized by release date under the "Calendar" link.*

Future missions will require systems that automatically identify scientific events in instrument data. Technologies currently under development in this area include trainable sunspot recognizers, detectors for craters and volcanoes, and systems that find natural satellites of asteroids. As part of ground-based systems, these technologies enable scientists to automatically mine vast volumes of spacecraft data for the information they need. Combined with onboard planning and execution, these technologies enable scientists to prioritize and summarize data on board, to scan high-rate data streams for short-lived or hard-to-find events, and to detect and exploit fast-breaking science opportunities, such as eruptions or solar flares, that would otherwise be lost.

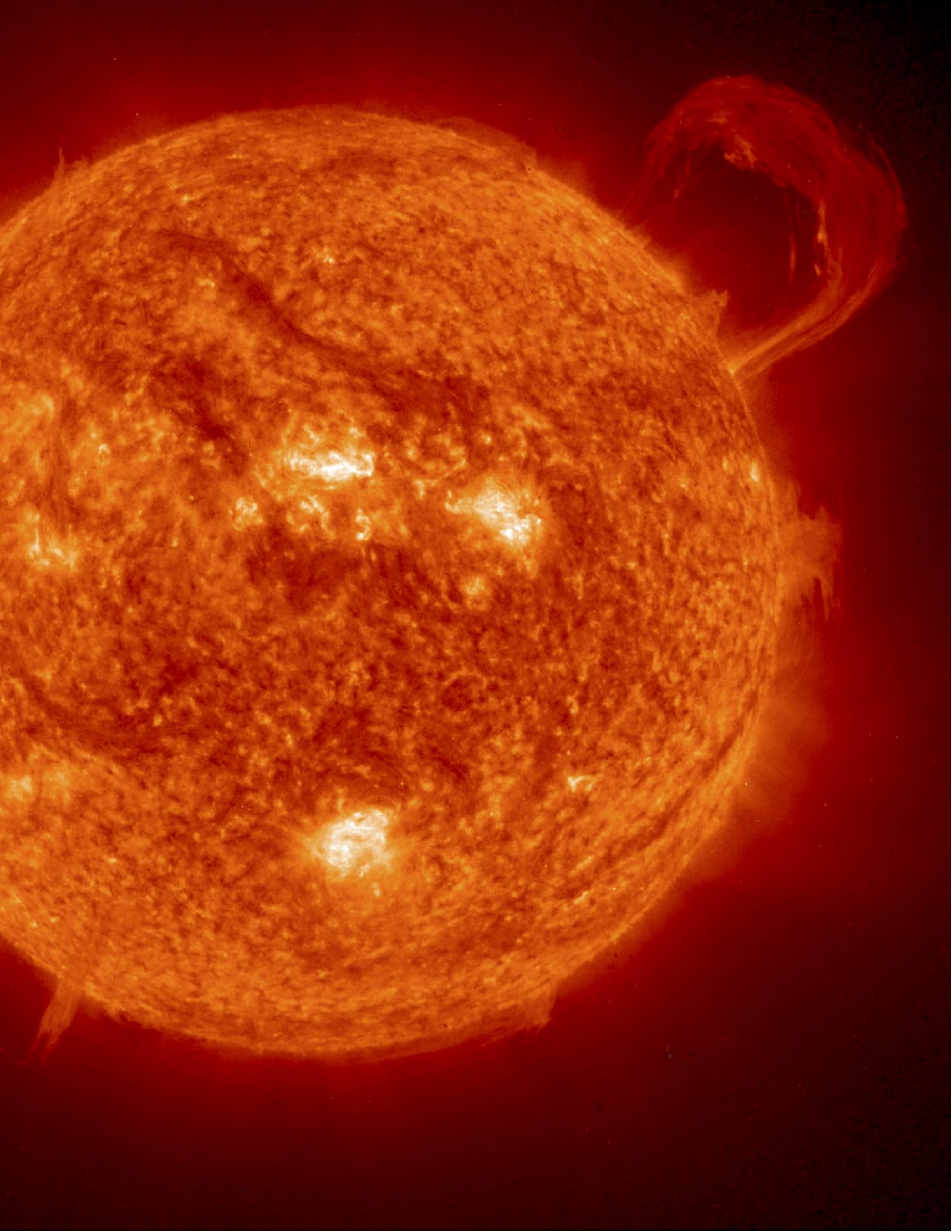
Intelligent Science Data Understanding

CURRENT RESEARCH

Reusable Pattern Recognizers for Solar Imagery

This task will develop image analysis technologies that automatically recognize scientifically relevant features in multispectral images, with an emphasis on solar imagery. System operation begins by using images labeled by scientists to learn a statistical model automatically for the features of interest. As new images are acquired, this model is coupled to general-purpose image-analysis software that integrates the resulting spatial cues to define local, pixel-level assessments of activity. These pixel-level cues are then progressively linked into a coherent, object-level scene description of the phenomenon of concern. The result is a directly interpretable summary of scientifically relevant information

Automated recognition and tracking of sunspot activity is essential for making full use of the large quantities of data generated by the SOHO mission. Identifying and tracking sunspots aids in understanding the dynamics of the Sun, which leads to improved understanding and prediction of our environment on Earth.



in the image. Our use of open standards for structured data (e.g., object models and datasets in XML with suitable schema) ensures portability across applications and future extensibility.

Onboard Science and Discovery Algorithms

This research is developing algorithms to find, analyze, and catalog spatial objects and dynamic events in large scientific datasets and real-time image streams. These include:

• Adaptive recognition algorithms that are trained from user-provided examples and can be easily customized to new domains without reprogramming.

• Novel techniques that enable a user to formulate and execute queries for objects within large image collections, based on models that are boot-strapped from single examples and/or sketches.

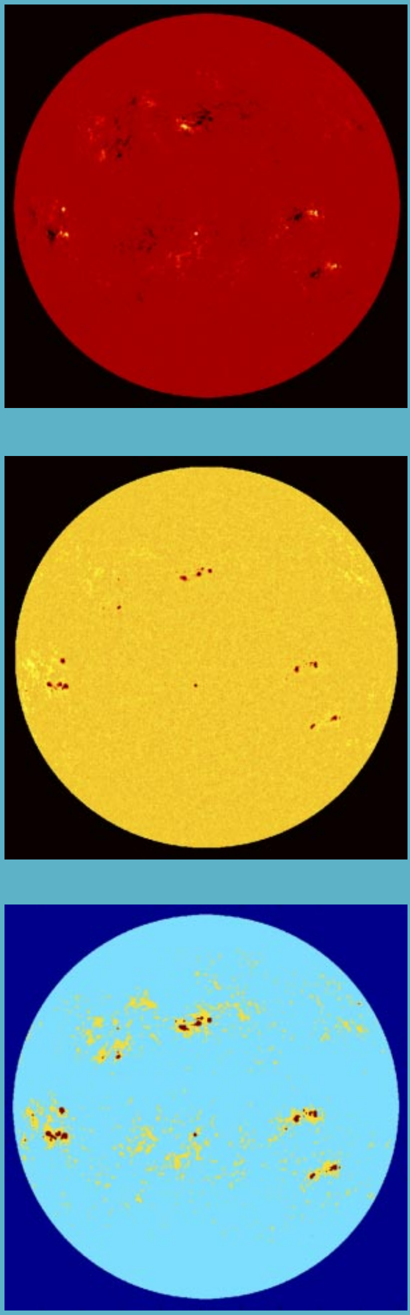
• Generic discovery algorithms that can autonomously identify “interesting” objects with no prior model.

• Processing techniques based on temporal motion coherence for change detection.

These pattern-recognition techniques are the core onboard processing technology for the Autonomous Sciencecraft Experiment (ASE), a New Millennium ST6 technology validation mission. ASE will fly on board TechSAT-21, an Air Force Research Laboratory satellite constellation scheduled for launch in 2004. ASE will demonstrate autonomous onboard recognition and retargeting of fast-breaking science events, and intelligent onboard science data selection and reduction to make the best use of limited downlink bandwidth. ASE is a collaboration including JPL, the Air Force Research Laboratory, Interface & Control Systems, Princeton Satellite Systems, Arizona State University, and the University of Arizona.

Onboard Pattern Recognition for In Situ Science

The science return of future robotic exploration missions can be enhanced by analyzing and prioritizing instrument data onboard. The primary goal of this research is to demonstrate a method for increasing the return of scientifically relevant information from a Martian surface exploration mission. The key to our solution is to enable



Solar and Heliospheric Observatory (SOHO) Michelson Doppler Imager (MDI) magnetogram in red, photogram in yellow, and our label-classification map in blue. The label map condenses the information present in each input image into a summary of the features present.

a new level of autonomy in the science discovery process by means of onboard data processing and integration. We are developing onboard intelligence sufficient to extract geologically meaningful data from visual images and spectral reflectance data of soil and rock samples, thus guiding the selection, measurement and return of scientifically important data from significant targets.

Knowledge Discovery Support System

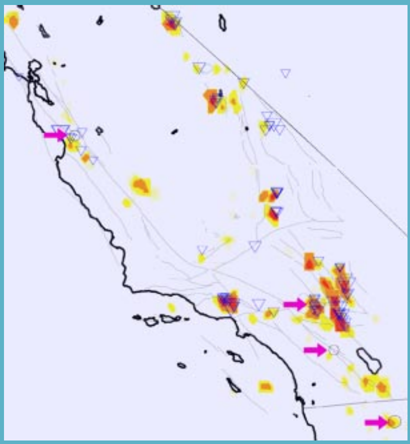
NASA missions have generated vast amounts of data, and current and future missions are expected to generate orders of magnitude of additional data. The volume of data necessitates the development of intelligent methods for information extraction and data understanding. In this project we are developing the capability of applying scalable data-mining methods and combining diverse information sources in support of knowledge discovery and data access. The objective of the task is to develop a discovery support system that generates, tests, and actively exploits hypotheses appropriate to a scientific domain. This system will move from a data-mining approach for analysis of large datasets to a predictive data modeling approach. Benefits to NASA include the ability to rapidly transform data from diverse and extensive data sets to generate knowledge and take actions.

Intelligent Time-Series Pattern Matching

We are developing effective search methods for large-scale time-series data, similar in spirit to World Wide Web text search-engines such as Google, but designed for mission sensor data (with more complex notions of "keywords"). For example, this technology will enable automated recall of relevant historic (mission, testbed, or simulation) behaviors (along with associated logs and analysis) similar to a current context of interest (e.g., new anomaly). This technology is intended for both onboard autonomy and ground-based mission operations. This work is being performed in collaboration with UC Irvine.

Knowledge Discovery from Simulators

Simulators play a fundamental role in investigations by scientists and engineers across NASA, the Department of Energy, the Department of Defense, the Federal Aviation Administration, industry, and academia. In many cases, simulators provide the means to examine processes that would be infeasible or impossible to study otherwise. We are developing techniques for data mining and knowledge discovery to enable efficient, in-depth exploration and exploitation of large-scale numerical simulators. We are emphasizing two science applications: (1) origins of the planets and long-term behavior of Solar System bodies, and (2) magnetospheric dynamics. Unlike traditional data mining, a unique aspect of this work is that the analysis is not confined to a static dataset; instead, the simulators can be used to generate new data leading to rich opportunities for active learning. This work is being performed in collaboration with the South West Research Institute.



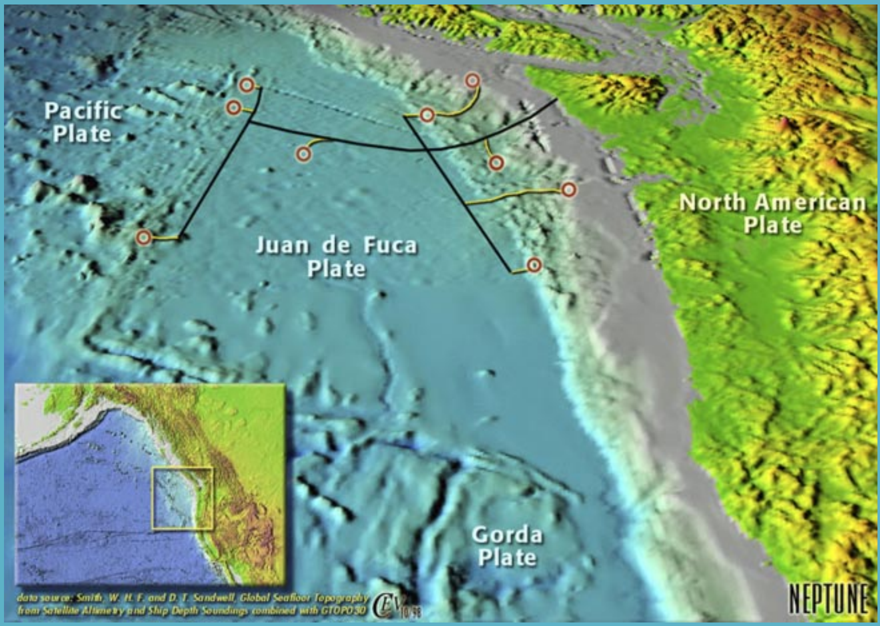
An earthquake forecast map. The colored anomalies are spots where large earthquakes are likely to occur according to our analysis, but are not guaranteed to occur. More research is needed to quantify how well we can localize these occurrences in time.

Forecasting Earthquakes in California

In the accompanying map, the yellow and red areas show a forecast of regions of California identified as likely to experience an earthquake of M>= 6. The red arrows represent the four M>= 5 earthquakes that have occurred since the original map was made. The algorithm that constructed this forecast used historical seismicity data up until the end of 2000. This and other data-mining methods under development allow investigators to explore relationships within datasets, pointing out correlations and prompting new questions to be asked. This work is being performed in collaboration with the University of Colorado and the University of California, Davis.

Project NEPTUNE: A Sensor Web on the Ocean Floor

Scientists are relying increasingly on sustained observations and interactive experiments to understand dynamic Earth and ocean processes. The goal of the NEPTUNE project is to establish a plate-scale submarine network of remote, interactive natural laboratories for real-time, four-dimensional (3-D plus time) experiments and observations on the Juan de Fuca Plate off the Pacific Northwest coast. One component of the NEPTUNE project is the development of a new infrastructure to support an extensive, remote, continuous, and interactive "sensor presence" within a particular natural laboratory of interest. The NEPTUNE system will provide power and communication links via fiber-optic/power cables to connect webs of sensors above, on, and beneath the seafloor with scientists, students, and the public on land. JPL's design of the power system is intended to deliver high power levels with the flexibility to grow. The novel approach taken



Project NEPTUNE's combination of cables, sensing instruments, and remotely operated robotic systems will facilitate an unparalleled long-term study of ocean and Earth processes.

for this system is based on the use of regulated power supplies, which automatically adjust to changing load conditions. A multilayered protection system makes the system as fault-tolerant as possible.

TECHNICAL CONTACT

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NEW TECHNOLOGY/ SOFTWARE

Algorithm for Autonomous Visual Discovery* — NTR #21107 (November 2001)

An Optimized Novel Propagation Algorithm and Software for Temporal Constraint Networks in JPL Mission Data Systems — NTR #21098

A Software Library for Parallel Adaptive Refinements of Unstructured Tetrahedral Meshes* — NTR #20948 (March 2001)

Infrastructure Software for Mining Image Data Bases* — NTR #20921 (April 2001)

Multithreading Program for Retrieval of Optical Phase Fields* — NTR #20848 (April 2001)

Program Summarizes Operational Data from a Complex System* — NTR #20822 (November 2000)

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Spacecraft, launch vehicles, aircraft, and complex ground systems are increasingly dependent on autonomous health management. Autonomy provides enhanced system safety and availability while reducing mission and operations costs. Autonomous fault protection also enables rapid fault recovery — critical for future rover or submersible missions. Onboard fault detection, diagnosis, reasoning, and response are essential for systems that must respond quickly to changing environments or react to fleeting science phenomena.

Autonomous System Health Technologies

CURRENT RESEARCH

BEAM: Beacon-Based Exception Analysis for Multimissions

BEAM is a complete method of data analysis for real-time fault detection and characterization. The BEAM architecture is composed of numerous unique components that permit fusion of sensor data, physics-based dynamical models of the system, symbolic models, and statistical models. BEAM is capable of fault detection and prognostics in nearly any instrumented system. Two important features make BEAM a superior approach: its broad range of applicability and its ability to detect and, in most cases, resolve anomalies that are previously unknown or unavailable for training. This approach has been used with sensor and computed data of radically different types,

The space shuttle main engine (SSME) being fired during an acceptance test. Temperatures inside the main combustion chamber can reach 6,000 degrees F, while the turbomachinery in the pumps rotates at up to 37,000 RPM. BEAM was used to detect subtle degradations and sensor failures during SSME acceptance tests.

on numerous systems, without detailed system knowledge or *a priori* training. Its flexibility and proven ability to reason about new events makes it particularly valuable for autonomous spacecraft where rapid onboard responses to a variety of unknown conditions are required.

State Diagnosis: Model-Based Diagnosis

System diagnosis, a necessary step in onboard fault protection, is the task of identifying faulty components after detecting a system fault. It arises whenever observations of the system's actual behavior contradict its expected behavior. Model-based diagnosis, one of the most disciplined and broadly used methods, focuses on the logical relations between system components, representing component functions and interconnections as a logical system. The task of diagnosis is then reduced to finding the minimal set of components that fully explains the observed inconsistencies. Unfortunately, current model-based diagnosis systems are severely limited in practicality due to complexity of application and reliance on algorithms that scale exponentially with system size.

We have made promising advances in developing two novel algorithms to overcome the combinatoric explosion. The first method reduces the diagnosis problem to a determination of prime implicants of monotone Boolean functions. Early results indicate that this method can provide a superpolynomial algorithm for the diagnosis problem, and thus enable solutions for problems of reasonable size. The second method is to translate the diagnosis problem to an integer-programming problem. This method allows us to utilize existing integer programming algorithms, some of which can handle problems with several thousand variables. Second, this enables us to extract bounds for the size of its solution without solving it explicitly. These advances will vastly increase the capability of onboard diagnosis, in terms of scale, speed, and accuracy, without increasing the difficulty of application or required computational resources.

Architecture for Autonomy: Active State Model

The Active State Model (ASM) is a framework to integrate new fault detection and isolation (FDI) paradigms with other necessary autonomy technologies to meet the need for automated fault detection, diagnosis, response, decision-making, and behavior in future intelligent systems. Borrowed from psychology, the definition of an active system is one that possesses a certain degree of autonomy from the environment. This autonomy allows the system to perform purposeful transitions or motions that are not directly controlled from the outside. To achieve this state, an active system must have self-identification, self-awareness, and self-intelligence capabilities. The ASM fuses fault detection and isolation (i.e., BEAM and SHINE [Spacecraft Health Inference Engine]), model-based diagnosis (i.e., state diagnosis), and recovery components (i.e., SHINE, planners) with physics-enhanced "gray-box" technology for self-identification and self-awareness. This provides a more robust, adaptable, and reconfigurable system for autonomy applications.

TECHNOLOGY DEPLOYMENTS

DSSC: Deep Space Network Autonomous Station Control

This task demonstrates the coherent combination of a planner and a diagnostician. This platform is a pathfinder for development of the DSN-CAE (Deep Space Network–Common Automation Engine). The DSN-CAE utilizes several JPL-developed components, such as CLEaR (Closed Loop Execution and Recovery) and the FDIR (Fault Detection Isolation and Recovery) module, which includes BEAM and SHINE. The approach uses CLEaR for assigned ground equipment command sequence generation and monitoring, control, and execution, and utilizes the FDI components for prognostics and diagnostics of the system. Both systems were successfully demonstrated, along with the FDI component's ability to detect and isolate (to the subsystem level) anomalies that it was not trained to detect.

IVHM: Integrated Vehicle Health Management for the Next-Generation Reuseable Launch Vehicle (RLV)

NASA's IVHM program for the second-generation RLV will lay the groundwork for this next generation of space vehicles. By integrating artificial intelligence with advanced sensor and communication technologies, we can build space vehicles that can reason, diagnose problems, and recommend solutions, giving human crews more time for the important work of exploring space.

The objective of this task is to deliver an Integrated Vehicle Health Management (IVHM) testbed to demonstrate autonomy technologies that reduce or eliminate unnecessary maintenance. This capability optimizes the performance of the RLV to meet mission objectives and thereby reduces recurring operational maintenance costs. Maintenance is only performed when needed as opposed to hours-in-use replacement philosophies. IVHM provides a far-reaching capability to maintain and service future reusable space transportation systems in a cost-effective manner. This technology has a high potential for payoff to future space transportation systems.

Deep Space Network Station 14 was one of the stations used to demonstrate the proof of concept environment for the DSN–CAE system.

TECHNICAL CONTACT

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NEW TECHNOLOGY/SOFTWARE

A Novel Real-Time System Performance Tracking Method Based on Constructive In-Line Estimation Using Couple Singular Dynamical System — NTR #20834

BEAM Next-Generation Exception Analysis: Integration of Signal-Based, Model-Based and Expert System Methodology — NTR # 21126

Dynamics of Intelligent Systems — NTR #21037

Novel Wavelet Based Real-Time Method for Robust Diagnostics in Aerospace systems with Hopping and Time Varying Drift — NTR #20830

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Earth and space science datasets are becoming larger, year after year. The scientific communities, and the larger public, are requesting greater access to these datasets. Previously hard to access, these datasets either exist within network-accessible archives or they are generated upon demand using high-performance computers. At JPL, we have developed ways in which these parties can interact with existing data through simple (often web-based) user interfaces, which hide the complexity of the computing required to analyze and visualize the datasets.

Creation, Analysis, & Visualization of Large Science Datasets

CURRENT RESEARCH

National Virtual Observatory

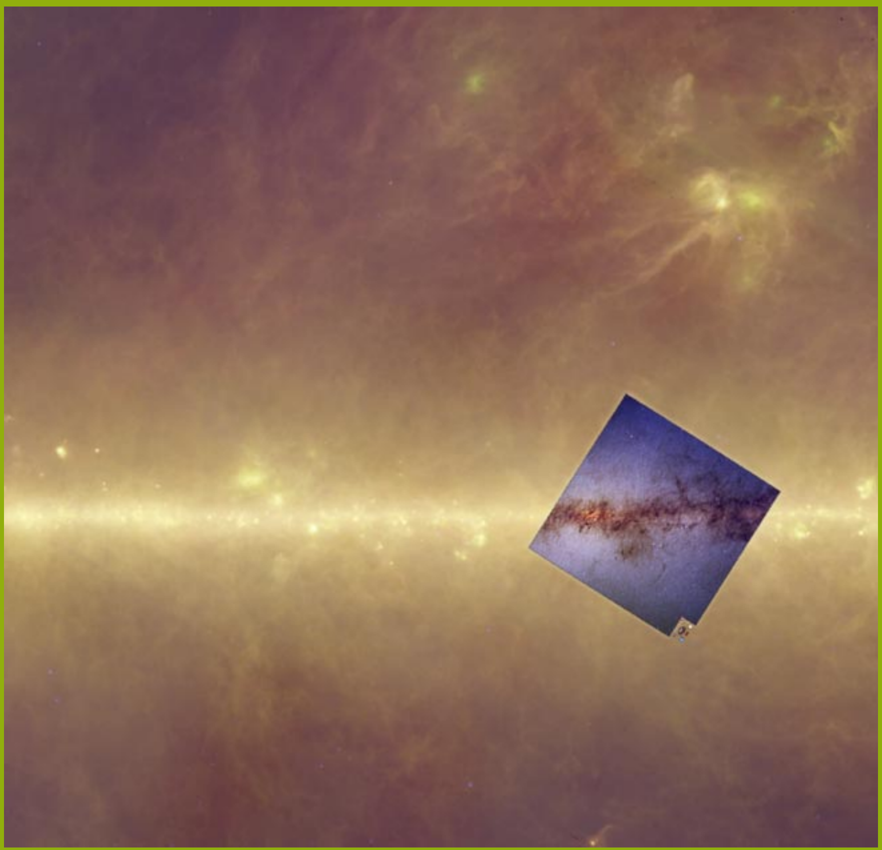
Using the yourSky custom sky image mosaic server (http://yourSky.jpl.nasa.gov/), a user can rapidly access arbitrary regions of the sky from member archives as a single FITS (a standard format for astronomical images) image, regardless of the native partitioning scheme of the archive. The Digitized Palomar Observatory Sky Survey (DPOSS) and the Two Micron All-Sky Survey (2MASS) are currently accessible with yourSky.

The server performs on-the-fly mosaicking of images while meeting user-specified criteria, including the dataset to be used, wavelength, position on the sky, coordinate system, projection, data type, and resolution. A web browser interface was built as part

The center portion of a 20-GB image mosaic of Andromeda constructed by yourSky from 18 DPOSS plates in two visible wavelengths.

of yourSky to allow access from the desktop for custom mosaic requests and mosaic retrieval on a common desktop machine with only the ubiquitous web browser as a client. The yourSky server maintains a database that is used to determine which images are required to construct a requested mosaic. The images are then automatically retrieved from their respective archive(s), and the mosaic is constructed rapidly using a high-performance parallel code. As this process is not currently fast enough to allow true interactive response, one of the items that the user supplies is an e-mail address. When the mosaic is completed, an e-mail is sent to that address to notify the user that the mosaic is complete and may be picked up. As such, yourSky represents an early module of the emerging National Virtual Observatory. NVO will be a collection of interoperable codes and data all living on high-performance computational "grids."

Demonstration of visualization of multiresolution, multispectral, geographically distributed astronomical datasets. Image server software delivers image tiles from each data site and the visualization client combines the data streams while providing smooth pan and zoom on massive images and astronomical catalog viewing capabilities.



Visualization and Animation of Terrain Data

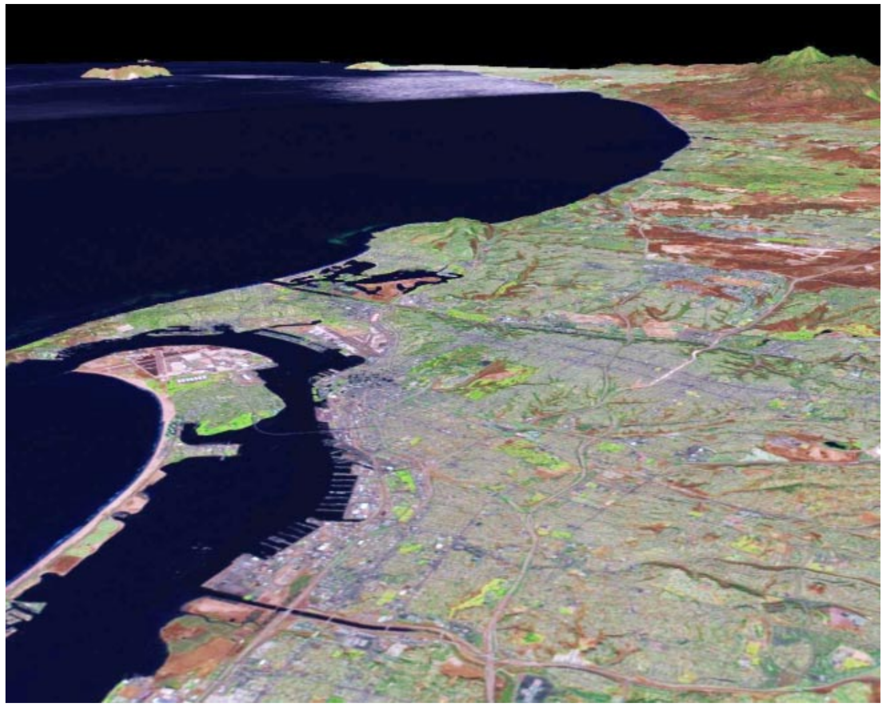
RIVA (Remote Interactive Visualization and Analysis) is a parallel terrain-rendering system for interactive visualization and exploration of large terrain datasets. It renders 3-D perspective views by overlaying Earth or planetary imagery on a digital elevation model. RIVA uses an efficient ray-identification algorithm, and is scalable to large machines, large datasets and large images, including the ability to render out-of-core. Multiple viewport rendering allows it to render an image as large as 3,000 × 4,000 pixels or more. RIVA includes a 2-D image and flight path viewing program and a keyframe preview feature to assist the user in designing and previewing a flight path.

JPL uses RIVA to build fly-over animated movies for scientific exploration and outreach purposes. During fiscal year 2001, we created two high-definition fly-over movies: a movie showing the principal natural hazards of San Diego and a Lewis and Clark trail movie following their 1804–1805 journey from St. Louis to the Pacific Ocean.

We also assembled a seminal HDTV production facility consisting of a SGI Onyx2 with HDTV capabilities, an HDTV VCR and an HDTV monitor. We then developed software for real-time playback of HDTV computer-generated frames, including technologies for lowering the required data bandwidth. We have created custom software for the New York–based American Museum of Natural History's (AMNH) HDTV production facility to simplify integration of Earth science data. AMNH is engaged in producing a series of HDTV "Science Bulletins" to be distributed to a number of museums and media outlets. This JPL–AMNH co-developed technology is an important component of this Science Bulletin work.

MAPUS (http://mapus.jpl.nasa.gov)

Map United States (MAPUS) is a JPL web site that is an example of a graphic, map-driven web-based interface that permits a user to interact with a very large dataset. The NVO project will use both the technology developed for MAPUS and that developed in yourSky (discussed above). MAPUS allows a user to view, pan, and zoom a mosaic image of the complete United States, using Landsat and elevation data. Additionally, a user can turn on and turn off overlays, which include state and county boundaries and rivers. The site usage is rapidly increasing, and many public users have provided positive comments about this new tool.



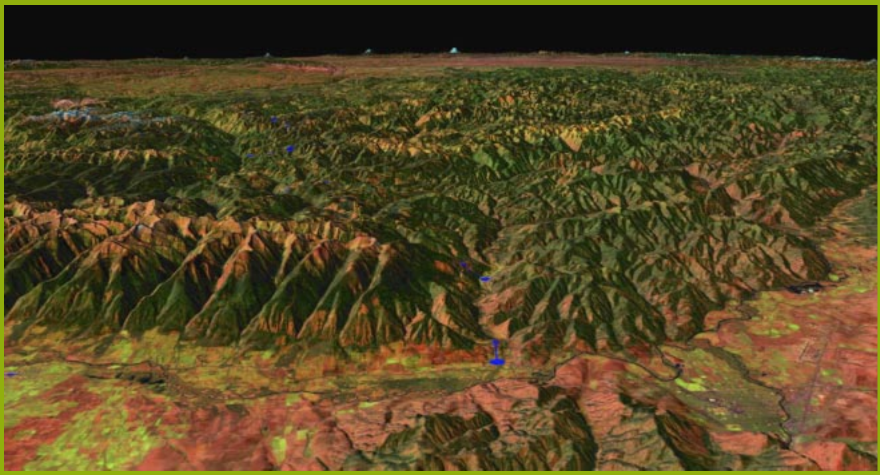
A sample frame from the movie "Principal Natural Hazards of San Diego," created with RIVA.

Mars Terrain Generation and Rover Simulation

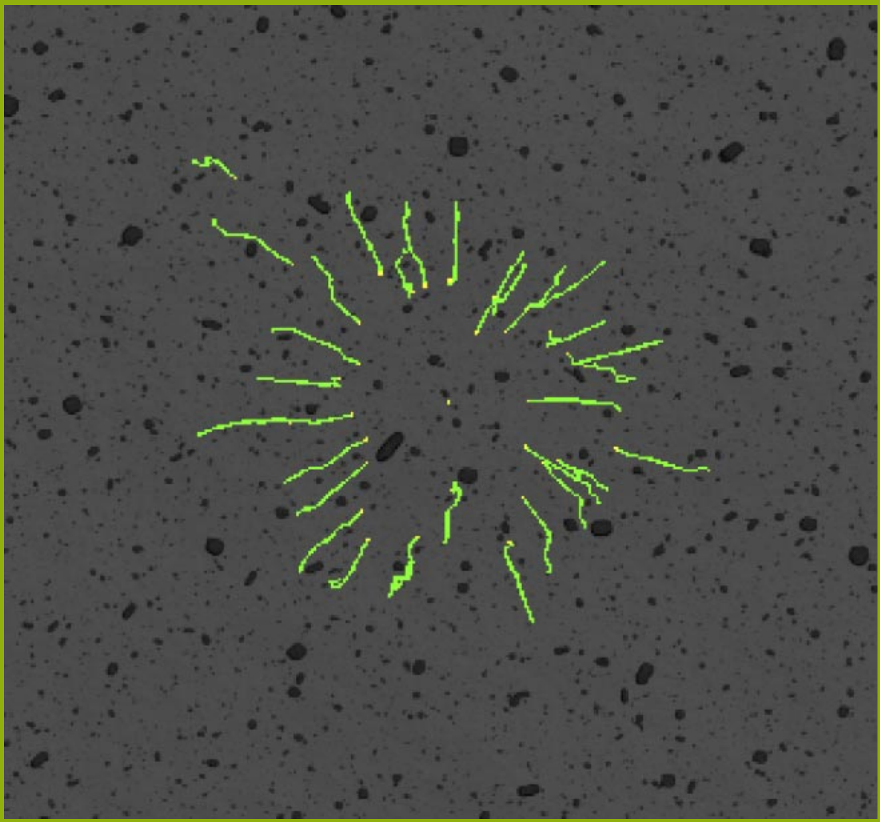
The Mars simulation work involves two main areas: synthetic terrain generation and rover simulation and visualization. These areas are clearly interrelated, and are part of a much larger JPL effort in simulation of the robotic Martian exploration, which in turn is part of the larger NASA effort of *in situ* exploration of the Solar System.

We demonstrated this past year the ability to build a terrain server to supply synthetic Martian terrain. This server can generate terrain with user-specified, large-scale slope distributions, craters, and rock densities to resolution as fine as 1 centimeter and for areas up to about 40 square kilometers. (We expect to eclipse the 40-square-kilometer limit shortly.) These capabilities have been certified by the Mars 2003 Project Scientist as reflective of the best statistical knowledge of the Martian terrain. The capability to ingest the best knowledge of the site-specific terrain as gathered by satellite observations will soon be productized as well. All of this runs efficiently and (relatively) quickly on JPL's institutional supercomputers, and can be served locally back to those same computers running simulations, delivered as bulk data files, or served as patches on demand over the networks to a client.

Our simulation efforts have focused on Martian rovers operating on simulated terrain. By employing parallel machines, many simulation trials can be executed at once. This provides an ideal environment in which to explore performance over a range of terrains, rover designs, and autonomous navigation algorithms. The results are fed into JPL risk analysis tools and are simulta-



A sample frame from the movie "Lewis and Clark: Search for the Northwest Passage," created with RIVA.



A still image from a multi-rover simulation. Multiple rovers are placed an equal distance from an objective and start toward the objective. The current position of each rover is a yellow dot, and a green trail marks the last 30 positions. Depending on the terrain, some rovers can advance faster than others.

neously visualized to increase human understanding of the simulations. Three separate rover navigation algorithms have been ported into the high-performance simulation framework.

TECHNICAL CONTACT

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NEW TECHNOLOGY/ SOFTWARE

Parallel Image Mosaicking Program — NTR #21121

Four Navigation Software Libraries: CCSDSTIME, TIMETRANS, NAVSYS-HP, and NAVSYS-SUN — NTR #20956

PUBLISHING OUR PROGRESS

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Quantum Computing Technologies

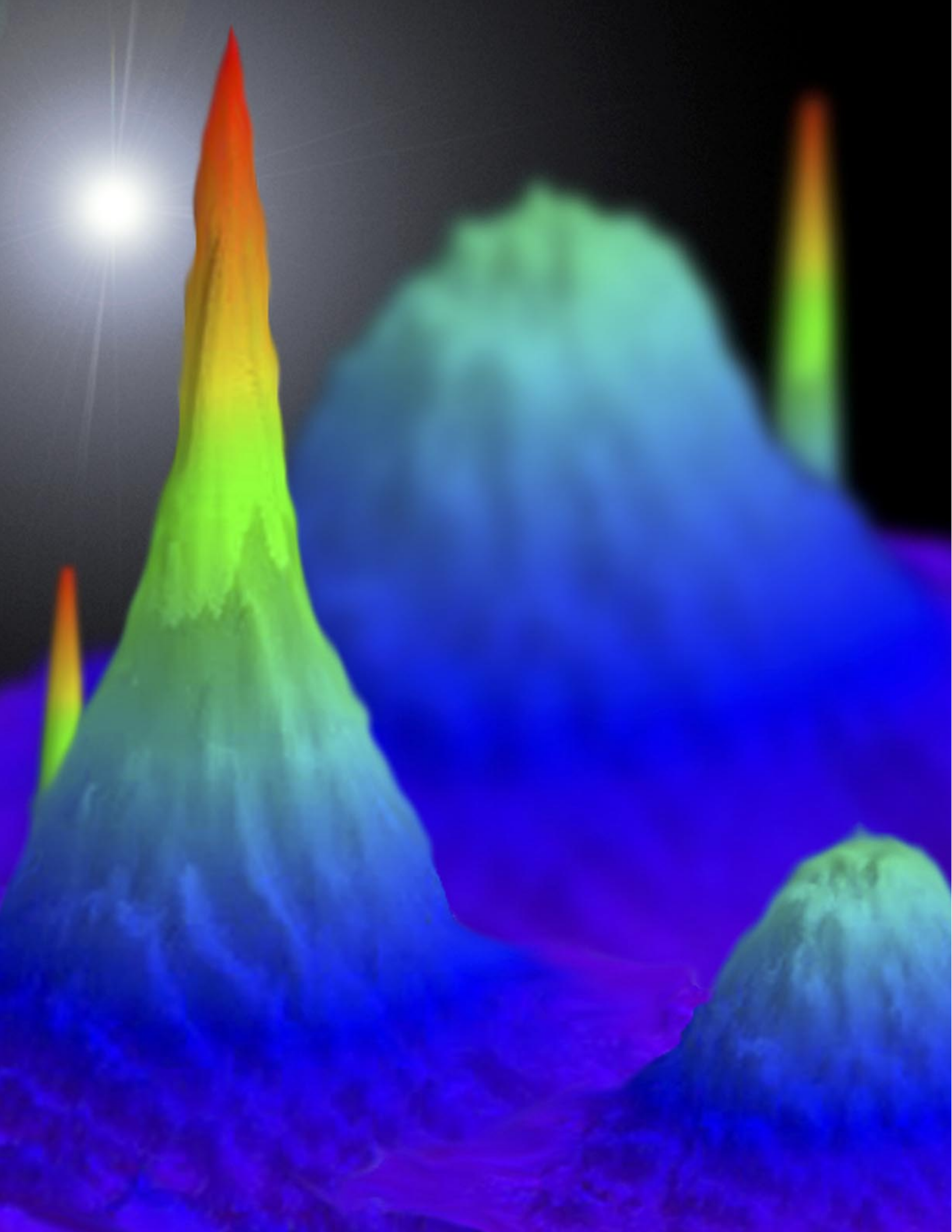
JPL researchers are working towards a new kind of computer based on quantum physics. Quantum computers will be able to solve problems that are intractable for classical computers, which could lead to breakthroughs in autonomous systems. Researchers are also developing an optical lithography technology that exploits the quantum nature of light to engrave microchip features much smaller than is possible with classical lithography. Smaller features yield higher transistor densities needed for faster, more powerful computers.

CURRENT RESEARCH

Quantum Information Theory

In parallel to the developments in quantum computing and cryptography, an entirely new science of quantum information theory has evolved that investigates the fundamental limits of how information can be processed in a quantum world. Due to nonlocal entanglements, which do not exist in classical information theory, all of the classical results have to be reworked to account for subtle quantum effects. There are now quantum versions of Shannon's theorem for channel capacity, as well as many other fundamental laws of a field that was hitherto only classical at its foundation. Investigations are underway at JPL and elsewhere in the areas of quantum data compression and superdense coding. In addition, quantum error-correction codes

Density distribution of cold, tapped atoms in a Bose–Einstein condensate (BEC). BECs are identified by the sharp peak in densities, here colored red.

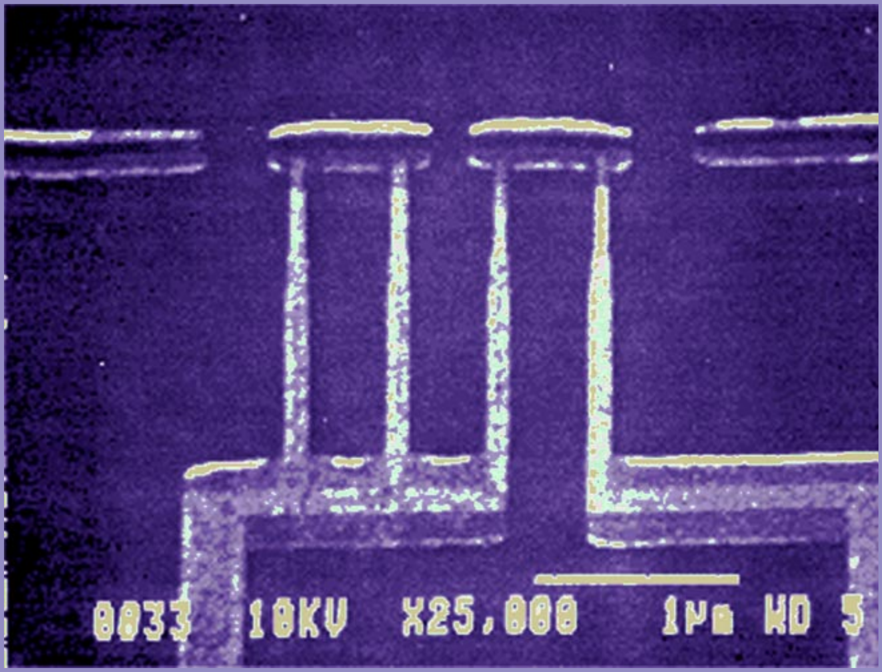


are being developed all over the world to ensure error-free operation of a quantum computer, once the technology is in place. The Quantum Computing Technologies group has a large program on extending quantum information theory to handle situations where Einstein's theory of relativity is important for such applications as orbital clock synchronization.

A related field of study is that of the effects of decoherence and noise on quantum circuits and communications channels. Early on it was recognized that a quantum computer might be realized in any number of disparate systems: ion traps, optical cavities, quantum dots, etc. It has become necessary to develop a general theory of environmental degradation effects on delicate quantum systems. These new techniques are fundamental and have direct application to the production of robust quantum sensors that rely on quantum effects, such as the quantum optical gyro.

Quantum Computer Hardware

With support from extensive theoretical calculations, it was suggested by a German group that superconducting Coulomb blockade devices would be very well suited as qubits — the basic building blocks for quantum computers. The Coulomb blockade devices have the very important advantage that they can be easily integrated to larger systems, since they are based on the microelectronics fabrication technology, which is very well advanced. These systems are macroscopic and can offer a macroscopically coherent quantum state from superconductivity. Until 1999 this concept was only theoretical, since quantum coherence had never been observed in this kind of macroscopic system. In a ground-breaking experiment, a Japanese group from NEC demonstrated macroscopic quantum coherence in a so-called single Cooper-pair box. The combination of these two very important results shows that it would be possible to implement the basic qubit operations in a Coulomb-blockade-based device. The decoherence time of a single qubit has been measured to be greater than nanoseconds, but the theory predicts a lifetime of milliseconds. With gate-switching



Electron micrograph of a radio-frequency single-electron transistor (RF-SET) that can be used to detect the quantum state of qubits, as they can have charges corresponding to a hundred thousandth of an electronic charge.

rates of picoseconds, this gives us the potential for tens of thousands of operations per coherence time. The Quantum Computing Technologies group is collaborating with the JPL Microdevices Laboratory on the experimental development of this hardware.

Quantum Algorithms

Our interest in quantum computing stems primarily from the need to solve hard, supposedly "intractable" (NP-complete) computational problems on a routine basis. Detailed mission planning, Deep Space Network communications scheduling, and spacecraft design optimization are just a few examples of the kinds of NP-complete problems that we face. All known classical computing techniques for solving such NP-hard problems require computational resources that, in the worst case, are exponential in the problem size. This means classical algorithms are either limited to small problems, or must employ methods that produce approximate solutions, or are occasionally unable to find a solution at all. Algorithms on quantum computers, however, may be able to solve these problems within computational resources that grow only polynomially with the problem size, which means they can solve very large problems that would be intractable on classical computers. This revolutionary computing capability would provide breakthrough improvements in numerous NASA and industry applications, ranging from onboard autonomy to design optimization.

Quantum Lithography

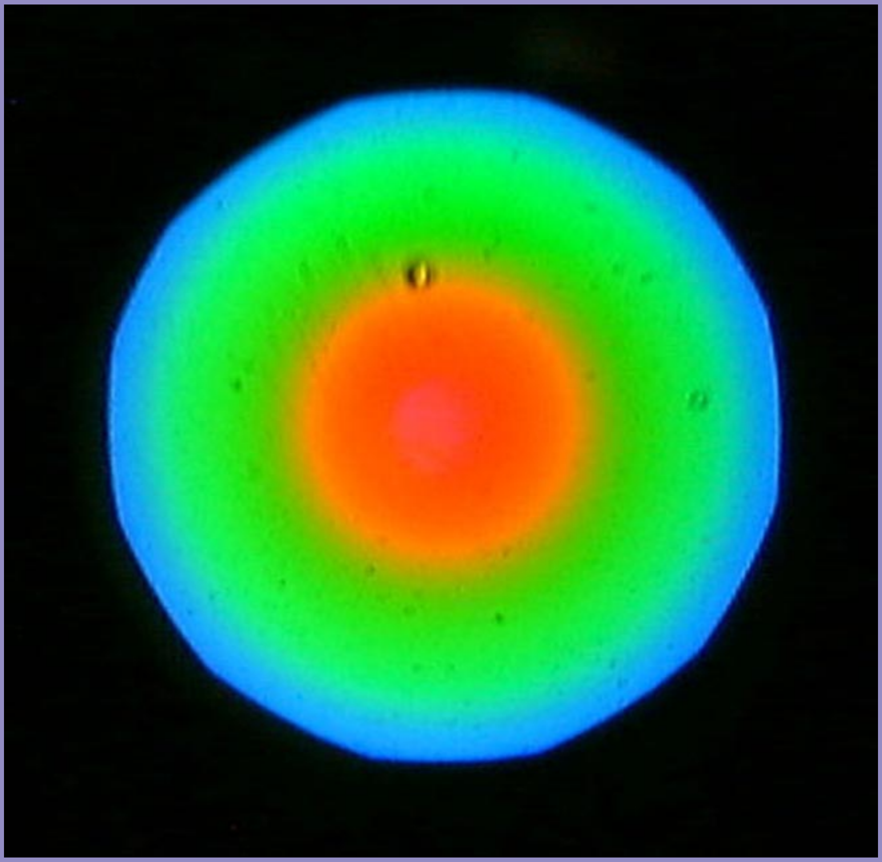
It has been known for some time that entangled photon pairs, such as generated by spontaneous parametric down-conversion, have unusual imaging characteristics with sub-shot-noise interferometric phase measurement. In fact, Fonseca et al. recently demonstrated resolution of a two-slit diffraction patterned at half the Rayleigh limit in a coincidence counting experiment. What we show is that this type of effect is possible not only in coincidence counting experiments, but also in real two-photon absorbing systems, such as those used in optical lithography. In particular, we have demonstrated that quantum entanglement is the resource that allows sub-diffraction-limited lithography.

Quantum Cryptography

While quantum computing is still in its infancy, quantum cryptography is here and now. In fact, European commercial interests are in the process of developing commercial quantum key-distribution systems. This technology is made possible by recent advances in single-photon, optical fiber engineering, which allows for the distribution of quantum entangled photons over hundreds of kilometers of optical fiber, or even in air, as in Earth to space. JPL is currently working on such a free-space system in the Quantum Internet Testbed. The quantum cryptographic keys distributed in this fashion are provably immune to attack, guaranteed by the Heisenberg Uncertainty Principle. This result, when coupled with the threat quantum computers now pose to existing public key systems, gives a new quantum way of transmitting secure data.

Quantum Hardware

It does no good to have quantum algorithms without a quantum computer to run them on. Tremendous progress has been made in developing the first rudimentary quantum logic gates, or quantum transistors. In particular, one of the first quantum logic devices was developed in Jeff Kimble's lab at Caltech in a single-atom, single-photon, high-quality optical cavity device. In addition, Dave Wineland's group at the National Institute of Standards and Technology (NIST), in Boulder, Colorado, has demonstrated quantum gates in laser-cooled ion traps. Also, the JPL Quantum Computing Technologies group and Microdevices Laboratory are developing scalable quantum logic elements in solid-state semiconductor devices such as quantum dots, quantum excitons, and superconducting quantum interference devices (SQUIDs). It is only a matter of time before the quantum version of the ENIAC computer is up and running, and all these developments in quantum algorithms can be put to work.



"Spooky" entangled photons in action. This is the first observation by the JPL Quantum Internet Testbed lab as it was brought on-line August 6, 2001.

Quantum Dots

Quantum dot–based computing in general, and quantum-dot cellular automata (QCA) in particular, have recently been investigated as promising new technologies capable of offering significant improvement over conventional very large-scale integrated (VLSI) circuits in terms of integration level, power consumption, and switching speed.

With regard to feature size, it is expected that QCA cells of few nanometers in size can be fabricated through molecular implementation. The drastic reduction in power consumption results from the fact that in today's VLSI technology, the information is transferred with the use of electric currents, that is, the transfer of charge. In contrast, the QCA represents a computation without current paradigm in which the information is propagated as a polarization state through local interaction among QCA cells. In this sense, the QCA also represents a wireless computing paradigm wherein, through local interaction among cells, a linear array of QCA cells can be used as a binary quantum wire. In terms of raw speed, it has been shown that a switching time of as fast as 200 picoseconds can be achieved.

TECHNICAL CONTACT

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Quantum Dots Cellular Automata (QCA) Fault-Tolerant Logic Gates: Block Gates with Imprecise Assembly — NTR #21127

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ry->cachelen/2) - 1;
```

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$filelen = (stat $f)[7];
$width = $filelen / (8 * $height
if ($width < 512) {
  $width = 512;
```

Award-Winning Technologists

THE ASPEN (AUTOMATED SCHEDULING AND PLANNING ENVIRONMENT) DEVELOPMENT TEAM received the NASA Honor Award for Group Achievement in June 2001. The citation reads: *In recognition of outstanding achievement in the design, implementation, and deployment of an advanced planning and scheduling system for spaceflight mission operations automation.* (June 2001)

JONATHAN DOWLING and the **QUANTUM COMPUTING TECHNOLOGIES GROUP** were honored as Top 10 Semi-Finalists in the 2000 *Discover Magazine* Awards for Technological Innovation. The award was for their work in advancing the field of quantum lithography through their "spirit of curiosity and ingenuity."

MIKE TURMON (second from left) was presented with the Presidential Early Career Award for new understandings in solar physics through cutting-edge information technology methods. (October 2000)

ANDREA DONNELLAN (below) received the Lew Allen Award for Excellence for exceptional research leadership and the development of new computational methods in the field of scientific data understanding systems, with applications to complex and varied natural phenomena in numerous scientific fields. (January 2001)

STEVE CHIEN was awarded the NASA Exceptional Service Medal in recognition of outstanding service and leadership in the development of automated planning and scheduling systems for space, and in the establishment of a world-class planning and scheduling lab at JPL. (May 2000)

Not only has Steve been honored as the Guest Editor for two *Artificial Intelligence Magazine* special issues on 2001 Applications of Artificial Intelligence, he is also serving on the ICAPS International Planning and Scheduling Executive Council.

The Jet Propulsion Laboratory just entered its fifth exciting decade of space exploration. JPL is located in Pasadena, California on 177 acres and employs over 5,000 people. It is managed by the California Institute of Technology for the National Aeronautics and Space Administration as a federally funded research and development center. The collegial atmosphere of the Laboratory and the unique mission of JPL and NASA attract the best and brightest from across the United States and from foreign institutions.

Our success is made possible by investments in critical technologies and research, a creative workforce, and collaborations with other NASA centers, government agencies, and university and industry partners.

U.S. industry has an excellent opportunity to leverage this expertise and investment. JPL has created a Technology Affiliates Program that has the responsibility to support U.S. industry by transferring unique expertise and cutting-edge technologies.

To learn more about this program, see the Technology Affiliates Program at *http://techtransfer.jpl.nasa.gov.* For information on how to take advantage of the opportunities that JPL can offer to you and your company, please contact the Technology Affiliates Office at (818) 354-3821.

The NASA Mission

To understand and protect our home planet

To explore the Universe and search for life

To inspire the next generation of explorers

... as only NASA can.

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